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COMMENTS ON FERRITE PHASE SHIFTER CONFIGURATIONS FOR THE MILLIM--ETC(U)  
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## 20. ABSTRACT (Continued)

However, many problems are encountered when attempting to scale efficient micro-wave ferrite configurations, particularly latching ferrite configurations, into the millimeter wave region. It is the objective of this report to review several ferrite configurations with the intent that consideration of these configurations may stimulate development of practical millimeter wave configurations. Ferrite phase shifter configurations that will be the subject of comment include the toroidal (dual slab), dual mode, Bush-Reggia-Spencer, and single slab configurations. Comments are also presented on a circulator used as a phase shifter.

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## COMMENTS ON FERRITE PHASE SHIFTER CONFIGURATIONS FOR THE MILLIMETER WAVE REGION

In the microwave region of the electromagnetic spectrum, electronically controllable ferrite phase shifters have demonstrated their value as components and as control elements for switches and attenuators. As the need for control components operating in the lower millimeter wave region increases, it is a reasonable approach to scale successful microwave ferrite configurations into the lower millimeter wave region (30 GHz to 140 GHz). However, many problems are encountered when attempting to scale efficient microwave ferrite configurations, particularly latching ferrite configurations, into the millimeter wave region. It is the objective of this report to review several ferrite configurations with the intent that consideration of these configurations may stimulate development of practical millimeter wave configurations.

One of the first problems encountered in scaling microwave ferrite configurations into the millimeter wave region is that of material limitations; to values on the order of 5000 gauss. While saturation magnetizations less than 5,000 gauss are adequate in the microwave region, this 5000 gauss magnetization limitation is partially responsible for reduced performance of millimeter wave, as compared to microwave, phase shifters. The impact of the present 5000 gauss magnetization limit will be illustrated during the discussion of the twin slab/toroidal ferrite phase shifter.

Several of the following ferrite phase shifter configurations will be the subject of comments. The toroidal and dual mode phase shifters which have demonstrated their value as latching (no holding current required) phase shifters in the microwave region. Both types can produce relatively frequency independent phase shift values over broad (over an octave) or reasonable (10 to 15%) bandwidths respectively. The Bush-Reggia-Spencer phase shifter, a configuration having frequency dependent phase shift, has been employed in the microwave region; while latching versions of this configuration have been built, employment of these rectangular waveguide configurations has been limited. Other configurations built or considered for the microwave region include latching circulators employed as phase shifters and single ferrite slab phase shifters in rectangular waveguide. These and other possible ferrite configurations are covered in limited depth in the following paragraphs.

Twin Slab (Toroidal) Ferrite Phase Shifter: This rectangular waveguide phase shifter, in two basic configurations, has advanced the state-of-the-art in the microwave region by virtue of its fast switching speed, differential phase shift essentially independent of frequency, high power capability, latching implementations and reasonable loss. Its nonreciprocal characteristics are of advantage in certain applications (e.g., switchable circulators). Due to its success in the microwave region, units have been built in the lower portion of the millimeter wave region and are available

commercially in the 30 to 40 GHz region; however, problems regarding fabrication and performance have been evident in the higher mid-millimeter wave region.

Since there are many articles<sup>(1)(2)</sup> in the open literature describing the design and operation of these units, no attempt will be made to repeat this information. A typical, though not optimized, X-band design (10 GHz) capable of operating over a 20% bandwidth will be scaled and calculations made to illustrate various problems currently encountered. Modeling of the toroidal phase shifter is based on the twin slab ferrite configuration of Figure 1(a). Figure 1(b) and 1(c) illustrate practical implementations of the basic model. The single toroid version of Figure 1(b) will be used for illustrative purposes even though the somewhat greater loss version of Figure 1(c) has advantages in the millimeter wave region since the drive wires for the toroids are in a lower electric field region and less likely to introduce moding, assuming that higher order modes can propagate.

Calculations of phase shift and electrical length were performed using a computer program based on the analysis of Clark.<sup>(3)</sup> In arriving at the design for the X-band configuration, the differential phase shift was to be essentially frequency-independent (less than 1% variation) over a 20% bandwidth, and, for case 1, only the dominant mode was to propagate, while, for case 2, the  $LSE_{11}$  and/or  $LSM_{11}$  modes would be capable of propagating. In practice, the  $LSE_{11}$  and  $LSM_{11}$ , if excited, could be suppressed by using an absorptive film orthogonal to the electric field as shown in Figure 2. The principal difference between case 1 and case 2 is the height of the waveguide with case 1 having the smaller value of waveguide dimension "b". Figure 3 illustrates the impact of height reduction on insertion loss of WR-28 rectangular waveguide. By analogy it is evident that reduction of the waveguide height for the ferrite-loaded configuration will also have an adverse effect on the insertion loss.

Table I indicates the dimensions of the X-band (10 GHz) toroidal phase shifter and scaled models designed to operate at 35, 60 and 95 GHz. Practical fabricability of the 60 GHz and particularly the 95 GHz units pose problems in regard to obtaining uniform dielectric-loaded ferrite toroids with space for a drive wire; it is difficult to place a reasonable diameter wire through the 0.221 to 0.140 mm toroid hole. Mechanical tolerances also become much more critical.

Table II indicates electrical characteristics of the principal X-band design and the scaled designs. Note that the scaled (desired) values of saturation magnetization are not available; thus 5000 gauss material was employed for the higher frequency designs. While the differential phase shift ( $\Delta\phi$ ) in the millimeter wave region is relatively constant, the average electrical length ( $\beta_{av}$ ) of the phase shifter increases at the higher frequencies as indicated by the ratio of  $\Delta\phi/\beta_{av}$ . In practice, loss increases when  $\Delta\phi/\beta_{av}$  increases.

Matching the toroidal phase shifter to the standard transmission line is usually achieved by use of quarter-wave dielectric sections. The number of quarter-wave sections increases as the bandwidth requirement increases; three (3) to four (4) sections are required for full rectangular waveguide band operation. Scaling of multistep transformer dimensions into the millimeter region could prove as much or more of a fabrication challenge than fabrication of dielectrics for center loading of toroids.

Dual Mode Phase Shifter: The dual mode phase shifter, a reciprocal phase shifter, consists of a nonreciprocal Faraday Rotator with a nonreciprocal circular polarizer at each end of the rotator. Matching transformers from rectangular to circular waveguide are also provided. Switching speeds are restricted by the shorted turns effect introduced by the waveguide housing. Latching circuits are provided for the Faraday Rotation Section. Figure 4 indicates a typical dual mode phase shifter configuration. Laboratory units of this type have been built to operate up to 60 GHz.<sup>(4)</sup> A major problem involved in design of these units at 95 GHz is concerned with implementation of the nonreciprocal polarizers. Bandwidths on the order of 15% have been achieved at microwave frequencies. Due to the field distribution within this unit, the conduction loss contributions toward total insertion loss is less than that of the toroidal phase shifter.

Bush-Reggia-Spencer Phase Shifter: This reciprocal ferrite phase shifter configuration<sup>(5)(6)</sup> has been successfully implemented at frequencies in both the microwave and millimeter wave regions. Units with 2% bandwidth are available commercially up to 110 GHz. A holding current is required for the millimeter wave units constructed. Again, due to the shorted turns effect, switching speeds are restricted. Phase shift produced by this configuration varies as a function of frequency and the bandwidth is restricted. While latching versions of this phase shifter has been built at microwave frequencies<sup>(7)</sup>, these units have had limited application.

Figure 5 illustrates several implementations of this phase shifter configuration and phase shift obtained from three (3) of the configurations<sup>(8)</sup>; cross-sectional views of the original configuration (Fig.5(a)), a modification of the original configuration (Fig.5(b)), a complementary configuration to that of Fig.5(b), (Fig.5(c)), a full height slab configuration (Fig.5(d)), and a modified full height configuration (Fig.5(e)). The configuration of Fig.5(a) has been successfully implemented into the millimeter wave region; bandwidths on the order of 2%. It is evident that there are no efficient paths in configurations of Fig.5(a) or 5(b) to conduct heat from the ferrite to the waveguide thus an average power limitation is incurred. Use of a ferrite slab, Fig.5(d), provides a heat link for the ferrite but is less efficient than the configuration of Fig.5(b). Fig.5(e) depicts a modification of the configuration of Fig.5(b) which increases the efficiency. Good ferrite-to-metal contact is essential to prevent generation of unwanted modes. The last configuration (Fig.5(e) and Fig.6) depict a configuration that may offer potential for the millimeter wave region. Inspection of Fig.5(f) indicates the phase shift characteristics of configurations 5(b) through 5(e) at X-band. Faster switching speed may be possible by slitting the waveguide to reduce the shorter turns effect<sup>(9)(10)</sup> while addition of yokes would allow latching operation over a portion of the millimeter wave region and/or allow operation with a holding field.

Latching Circulator Phase Shifter: A phase shifter configuration that may be of limited use in the lower millimeter region is shown in Fig. 8. This reflection-type configuration consists of a junction circulator with two ports terminated. The magnetization applied to the three-port junction circulator is varied, either via use of an electromagnet or use of a latching circulator, thus diverting different amounts of energy into each of the two (2) shorted arms. Maximum phase shift would be obtained when the magnetization is approximately that required for circulator action. This configuration, which was initially implemented in shielded triplate in the lower microwave region,\* is considered of limited applicability due to the limitations imposed on the circulator by saturation and remanent magnetization limitations. Fig. 7 indicates X-band measurements with this configuration; a circulator designed for use with permanent magnets was employed with an electromagnet replacing the original permanent magnets. The magnitude of the phase shift is, in part, dependent on the length of the shorted line sections.

Single Slab Ferrite Phase Shifter: Use of a single ferrite slab with transverse applied field can also produce nonreciprocal phase shift. While this configuration may not be as efficient as a dual slab configuration, implementation at millimeter wave frequencies may be easier. A toroid in waveguide is not required (only ferrite and dielectric slabs are required) and the drive wire is part of the external circuit as is the case with dual mode phase shifter configurations. Moding potential is thus reduced at the expense of remanent magnetic field.

Figure 9 indicates the configuration with two (2) dielectric materials ( $\epsilon_1$  and  $\epsilon_2$ ) one of which may be air. Figure 10 indicates measured phase shift for one combination of ferrite and dielectric. Calculated differential phase shift for this configuration was from  $361^\circ$  at 9.6 GHz to  $344^\circ$  at 12 GHz. Based on analyses, a broadband configuration is feasible. An adhesive could be used to form a ferrite-dielectric loaded waveguide which could be metalized. Additional efforts are anticipated in regard to adapting this configuration to the millimeter wave region.

Fin Line Phase Shifter: A fin line isolator has been built(11); this introduced the possibility of developing a fin line latching phase shifter. Figure 11 indicates the fin line isolator. A ready extrapolation of the isolator design to a latching phase shifter design is indicated in Figs. 11(a) and 11(b). Since, in practice, a waveguide-type housing is present about the fin line so that only one (1) mode would propagate, this configuration would reduce to a configuration which would be similar to that of a waveguide with an internally located ferrite toroid. Similar problems with regard to higher order modes, toroid size and tolerances would be present. It was thus decided that additional in-house efforts on this configuration would have a low priority.

In summary, several ferrite phase shifter configurations have been considered for use at millimeter wave frequencies. No practical implementations of latching configurations are currently available in the mid-(90 to 140 GHz) millimeter wave region. The most efficient microwave latching configurations are under investigation by commercial organizations. Bush-Reggia-Spencer phase shifters requiring holding magnetic fields are available through 110 GHz. Additional configurations are under investigation.

\* Unit was developed by Hughes Aircraft Company under Navy contract.



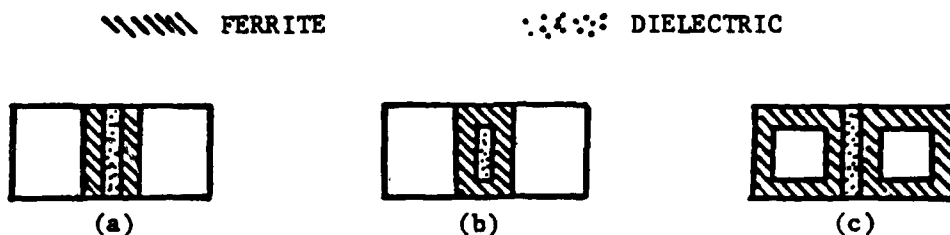


Fig. 1 - Twin slab, "toroid," phase shifter configurations

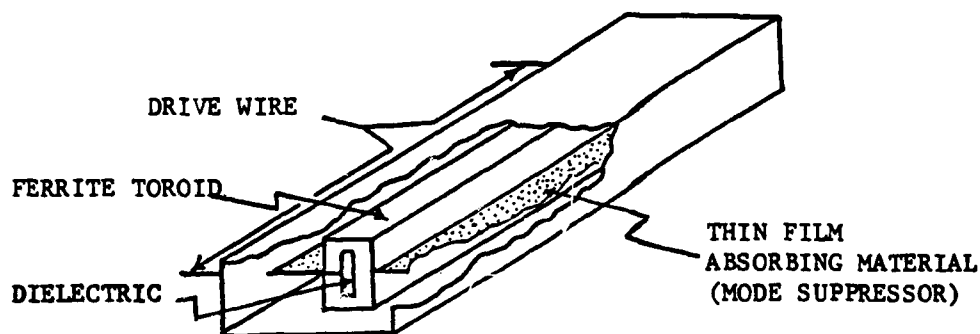


Fig. 2 - Ferrite toroid with thin film absorbing material in place

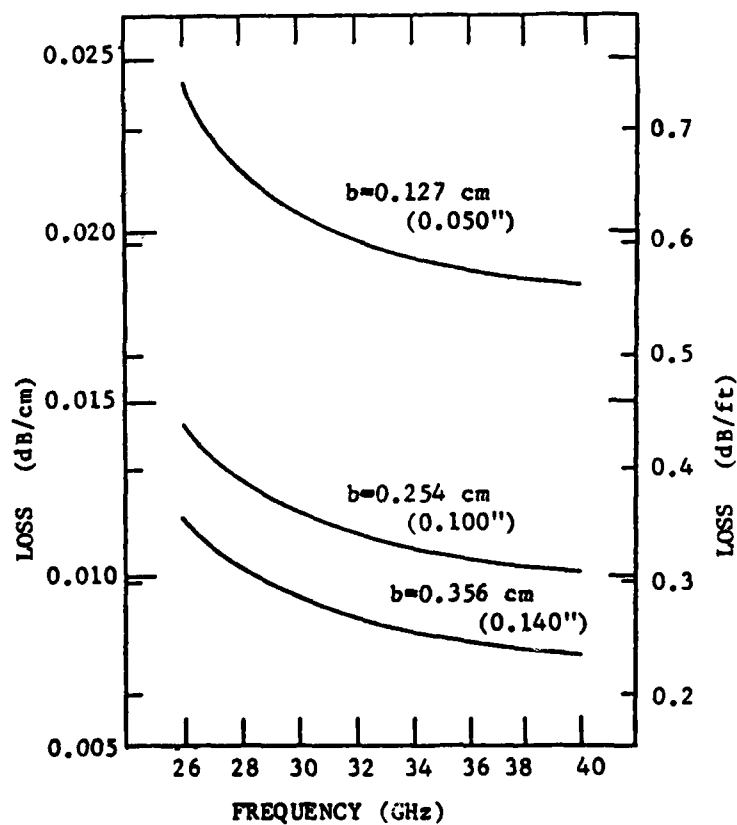


Fig. 3 - Waveguide loss for three values of waveguide height (b)

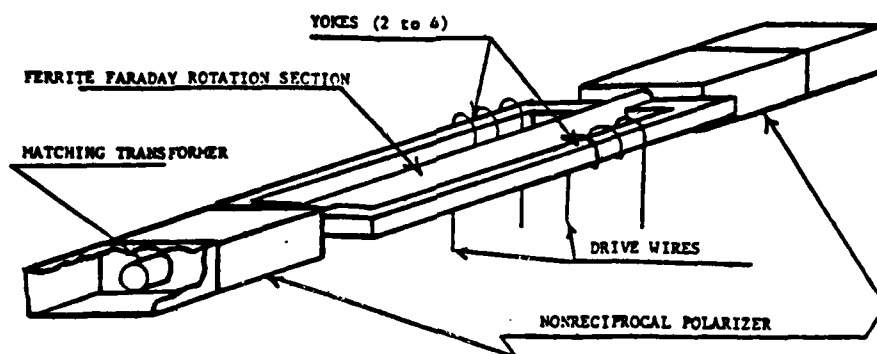


Fig. 4 — Dual mode phase shifter

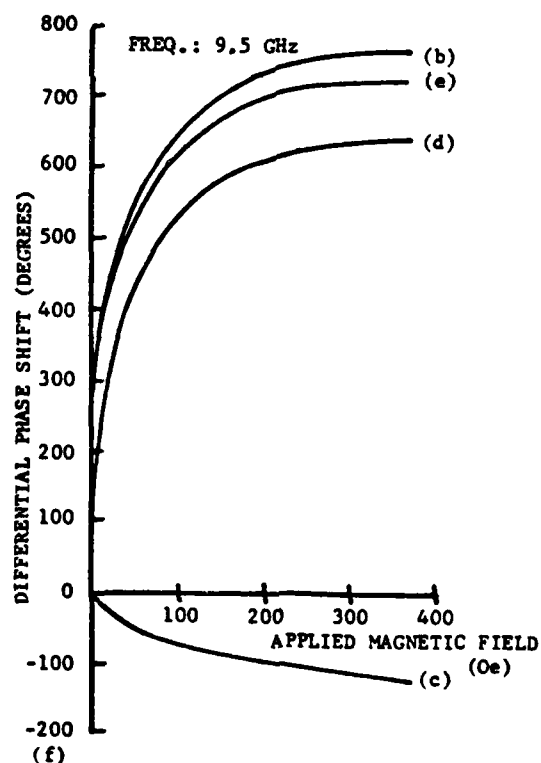
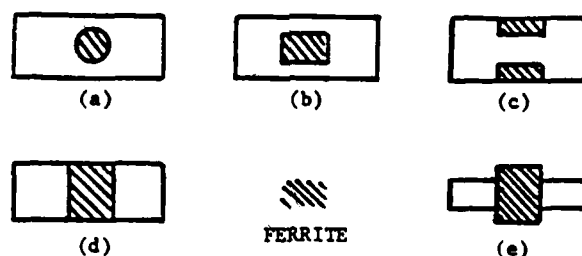


Fig. 5 — Differential phase-shift dependence on applied magnetic field for four waveguide configurations. In all cases the ferrite-slab width is 0.250 inch and the applied magnetic field is along the waveguide axes.

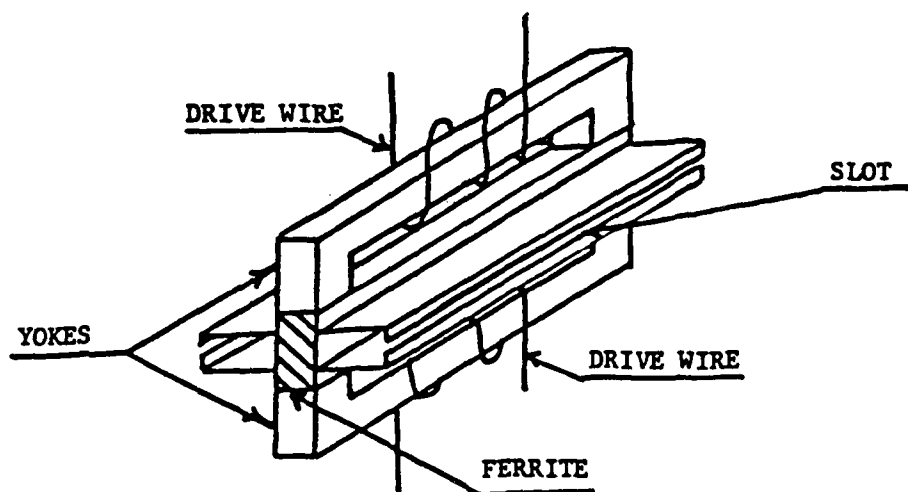


Fig. 6 — Suggested millimeter wave ferrite phase shifter configuration

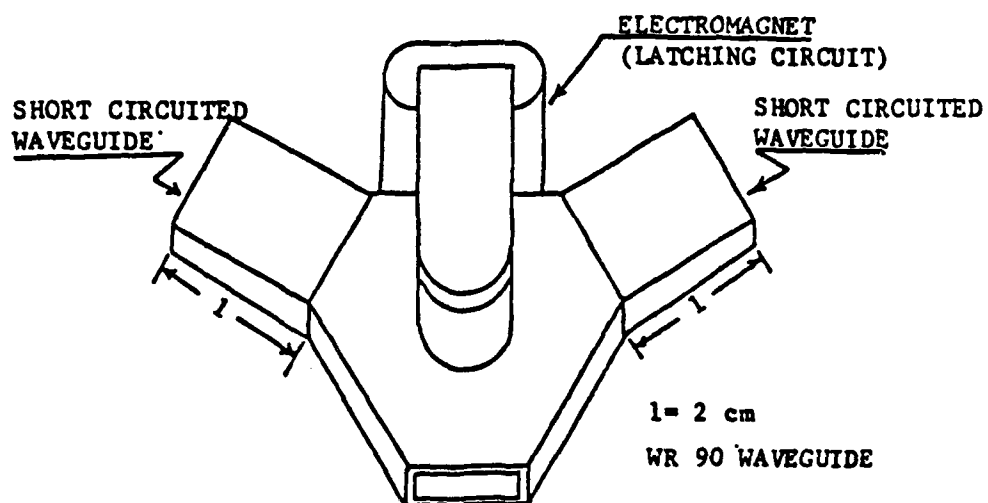


Fig. 7 — Circulator - phase shifter

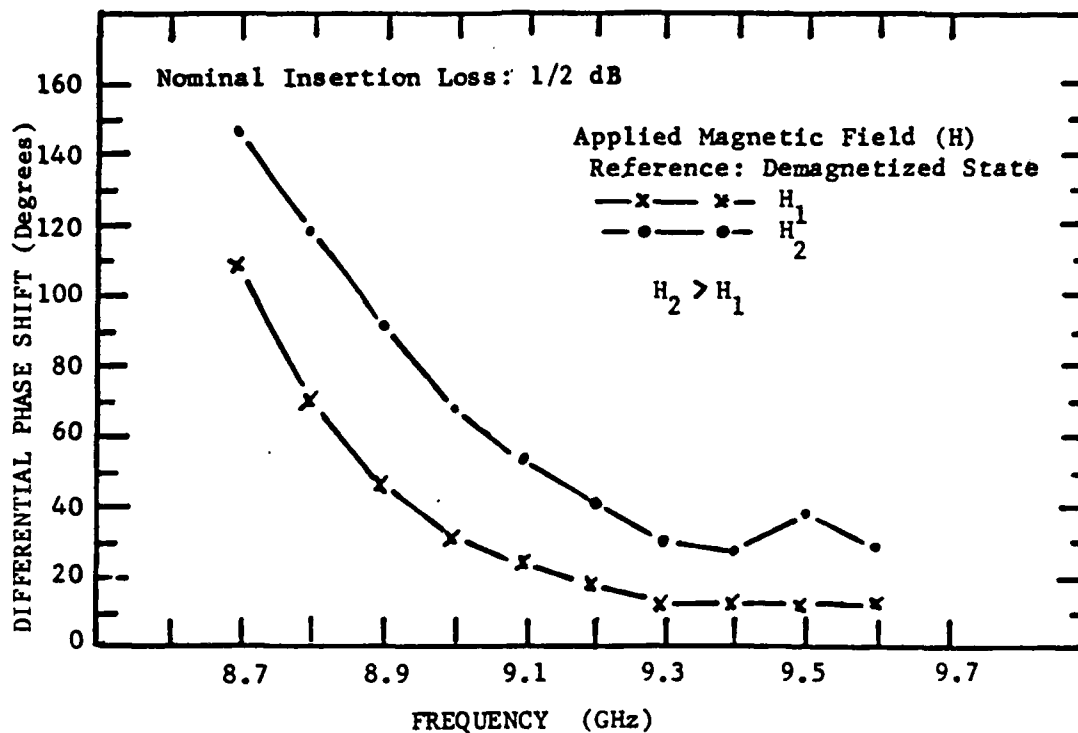


Fig. 8 — Differential phase shift for circulator-phase shifter as a function of frequency with applied magnetic field varied

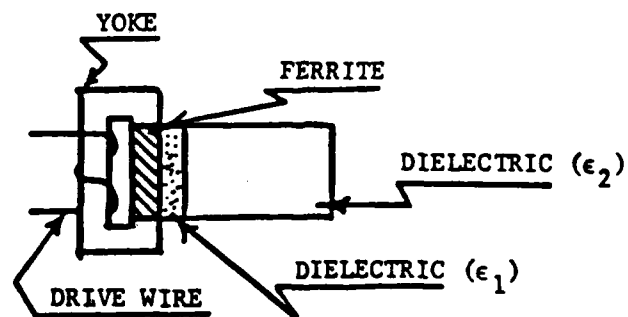


Fig. 9 — Single slab ferrite phase shifter configuration

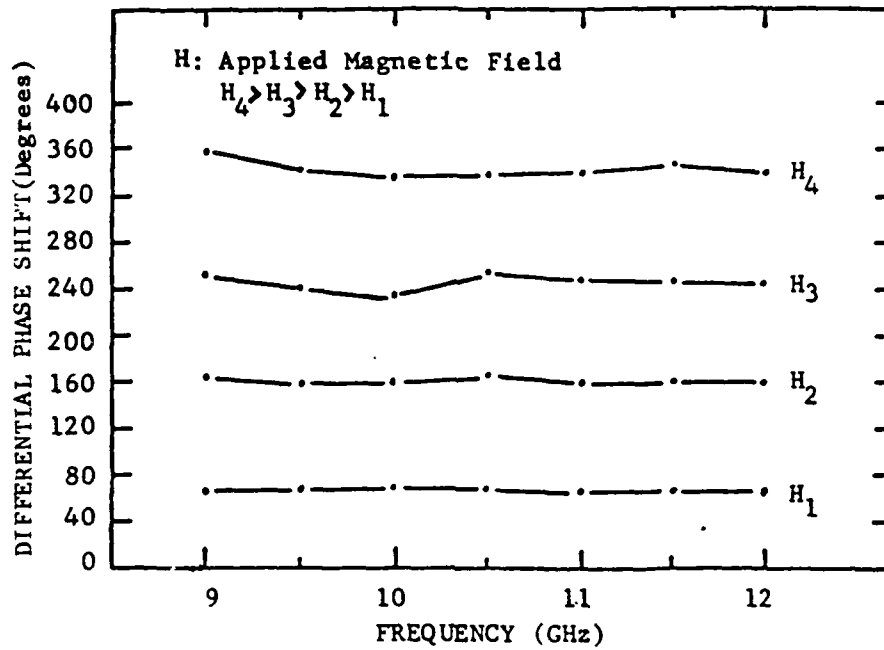


Fig. 10 — Differential phase shift of a single slab phase shifter as a function of frequency and applied magnetic field

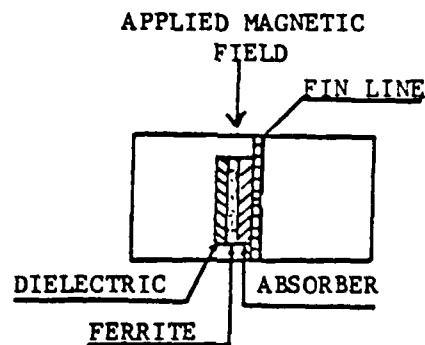


Fig. 11 — Fin line isolator

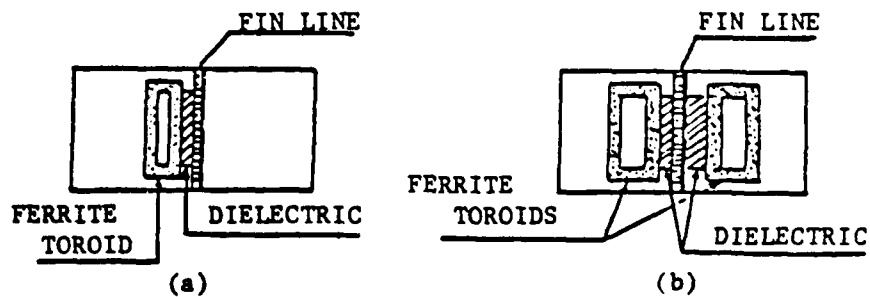


Fig. 12 — Fin line latching phase shifters

TABLE I

(All dimensions in mm unless otherwise indicated)

Center Design Freq.	a	b <sub>1</sub>	T	w	s	b <sub>2</sub>
10 GHz	12.446 (0.490")	4.445 (0.175")	4.365 (0.172")	1.524 (0.060")	1.321 (0.052")	8.890 (0.350")
35 GHz	3.556 (0.140")	1.270 (0.050")	1.245 (0.049")	0.432 (0.017")	0.381 (0.015")	2.540 (0.100")
60 GHz	2.075 (0.0516")	0.739 (0.0291")	0.729 (0.0287")	0.254 (0.010")	0.2211 (0.0087")	1.481 (0.0583")
95 GHz	1.311 (0.0516")	0.467 (0.0184")	0.424 (0.0181")	0.460 (0.0063")	0.140 (0.0055")	0.935 (0.0368")

TABLE II

( $\Delta\phi$  = Differential Phase Shift;  $\beta$  = Electrical Length)

Center Design Frequency	b(mm)	Desired $4\pi M_s$	Utilized $4\pi M_s$	$\Delta\phi^\circ/\text{cm}$	$\Delta\phi/\beta_{av}$	Cutoff Frequency (GHz)		
						LSE11	LSM11	LSE20
10 GHz	4.445	2000	2000	366	0.171	11.4	13.4	11.0
	8.890	2000	2000	366	0.171	7.0	9.8	11.0
35 GHz	1.270	7000	5000	892	0.118	40.1	46.9	38.6
	2.540	7000	5000	854	0.115	24.6	34.3	38.7
60 GHz	0.739	12000	5000	884	0.067	68.8	80.3	66.0
	1.481	12000	5000	847	0.066	42.1	58.6	66.1
95 GHz	0.467	19000	5000	880	0.042	108.8	127.1	104.6
	0.935	19000	5000	843	0.041	64.9	91.0	104.8

### Acknowledgment

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